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Woven Fabrics in Book Conservation: an Investigation into the Properties of Aerolinen and Aerocotton

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Abstract

Woven fabrics commonly referred to as 'aerocotton' and 'aerolinen' are frequently used in the conservation of books and manuscripts and are valued for their strength and flexibility. Although textiles have a long history in the production and repair of books, aerocottons and aerolinens are relatively recent materials adopted from early aircraft production. In 2007 the main supplier of these woven fabrics to the UK conservation community ceased production, and new producers started supplying a range of woven fabrics under the labels of 'aerocotton' and 'aerolinen'. Understanding the strength, composition and longevity of repair materials is central to conservation practice and this investigation tested two linens and two cottons alongside the discontinued cotton to quantify the relative strengths of the fabrics. Each fabric was tested before and after laundering, and in three directions (warp, weft, and bias). The tests conducted measured mass per unit area, thickness, sett, tensile strength, folding endurance and dimensional change. In tensile strength tests the bias-cut fabrics were weakest but extended the most, whilst those cut in the weft direction were strongest. The cottons lasted longest in terms of folding endurance and the samples cut on the bias were the fastest to break. The dimensional change tests showed that washing affected the linens more than the cottons, and that across all fabrics there was a greater amount of shrinkage in the warp direction. It is hoped that these results will provide concrete information to guide conservators in the preparation and use of aerocottons and aerolinens.

Introduction

Woven fabrics in book conservation

Woven fabrics have long been used in the production and repair of books and manuscripts, from covering materials to spine linings (Gehner 1989; Husby 1990; Minter 1985). Since the 1980s the use of fabrics commonly referred to as 'aerolinen', 'aerocotton' or 'airplane linen' has become widespread (Neville 2016; Clarkson 1992). Originally employed in the manufacture of aircraft (Arville 2015), it is their flexibility and strength, along with good fold endurance properties and tensile strength that have rendered them so valuable to conservators. Samuel Lamont & Sons Ltd had been the main supplier to the conservation community in the UK, but in 2007 ceased to produce aerocotton and aerolinen and conservators had to turn elsewhere for their supplies. It was the change of supplier and the lack of recent, independent scientific testing that prompted the authors to undertake this investigation. Two aerocottons and two aerolinens were selected for testing alongside the previously available Lamont aerocotton, purchased in 2006. The aim was to run a series of tests to produce a body of results on which conservators can base their choice about laundering, grain direction, and type of fabric when selecting a woven aerolinen or aerocotton.

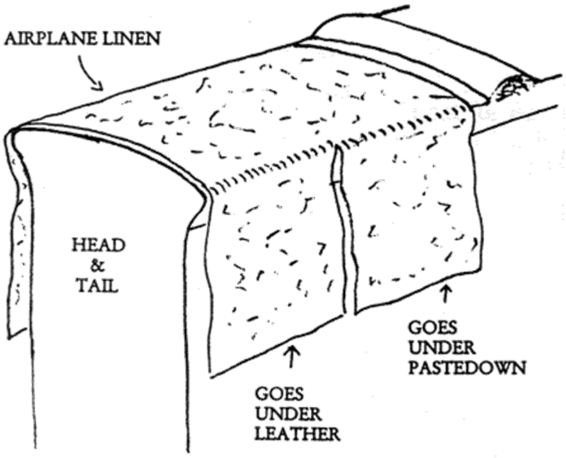


Figure 1: Illustration of woven fabric as a spine lining with extensions for a board attachment, reproduced with permission of the Licensor through PLSclear (Kite and Thomson 2006).

Woven fabrics are frequently used in book conservation, in particular as part of a board reattachment treatment and as a spine lining (Fig. 1). This often results in an applied mechanical stress to the fabric, due to the repeated joint action of the board where the fabric is forced to bend and flex and to the force of gravity pulling down on the textblock. Taking these factors into consideration, it is important to measure the strength and durability of repair materials in order to understand how they may perform. Many woven fabrics used in conservation are marketed as 'aerolinen' or 'aerocotton' but do not adhere to a common standard or share the same physical properties, and neither are these terms found in the British Standards Institute specifications for woven fabrics suitable for aerospace production (British Standards Institute 1992a; British Standards Institute 1992b). The materials currently available to conservators in the UK exhibit a range of properties, demonstrating the importance of independent testing.

Two principal studies have set the groundwork for measuring the tensile strength and folding endurance of woven fabrics used in book conservation (Sawicki 2009; Zimmern 2000). While they have provided a useful reference point for this investigation, their tests included materials that are now discontinued and unavailable and worked with a limited number of replicates. Specific use and treatment of the fabric varies according to individual practise. There is no universal approach that sets out an "ideal" direction (warp, weft or bias) of the fabric or its treatment prior to use (e.g. laundering, dyeing). Preliminary studies ('Conservation DistList' 2003; Sawicki 2009) on pre-conservation treatment of fabrics suggest that not all conservators launder the material before use, and there is evidence of fabrics used in all three directions (Puglia 2017; Kite and Thomson 2006).

Cotton and flax fibres

The essential building block in both cotton and flax (the fibres used in the fabrics tested) is $I\alpha$–cellulose. The cellulose molecule is formed of long chains with a high molecular weight and high degree of polymerization (DP) (Fig. 2) (Textile Institute 2007).

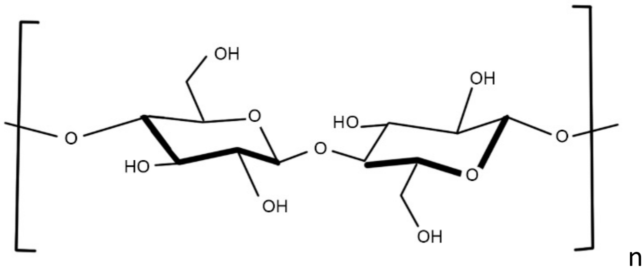


Figure 2: Principal drawing of two β-1,4-D (+)-glucopyranose in the chair formation linked by the 1,4-glucodic bond, Cellubiose unit, that makes up the long cellulose chains.© Lydia Gallup Aikenhead.

These long chains line up parallel to one another so that the OH-groups form vast numbers of inter-molecular and intra-molecular hydrogen bonds (Textile Institute 2007; Matthews et al. 2011).

Cotton

Cotton fibres come from the seed heads of the cotton plant (*Gossypium*) and can measure 25 to 60 mm in length depending on the species and growing conditions (Textile Institute 1975). Each fibre is a seed hair and consists of an outer protective cuticle, a primary wall, a secondary wall and a lumen. During development, cotton fibres contain approximately 85% cellulose, waxy substances, proteins and pectin (Liu, Y. 2018). As the secondary wall thickens with maturity, crossing layers of fibrils are added in alternating directions in a helical rotation. When cotton fibres dry out the initially round-shaped fibre collapses into a flat rotating ribbon-like shape with frequent alternating s and z twists or convolutions that are determined by the alternating direction during growth (Textile Institute 2007) (Fig. 3). With respect to mechanical properties, the key part of the fibre is the secondary wall which consists of almost 100% Iα–cellulose, with a DP of up to 14 000, uniform molecular weight distribution and a 2:1 ratio of crystalline to amorphous arrangements within the molecular chains (Textile Institute 2007).

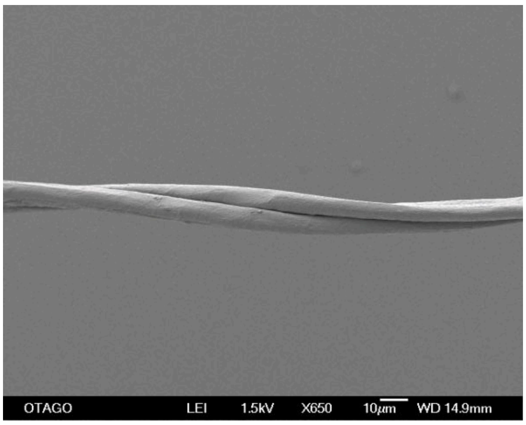


Figure 3. SEM Friebe aerocotton, surface of single fibre.
Under magnification, the individual cotton fibres have a smooth, ribbon-like appearance with convolutions along their length. Image courtesy of Liz Girvan, Otago Micro and Nanoscale Imaging, University of Otago.

Cotton yarns are often mercerized to improve lustre, dye uptake, and reduce fabric shrinkage. Mercerization uses a strong alkali (NaOH) which swells the fibres; drying is conducted under tension which results in fibres with reduced twist. Cotton fibres fracture in a diagonal twist following the angle of the helical rotation of the fibres in the secondary wall (Hearle 1989). The untwisting of the convolutions due to mercerization can result in weak points, reducing the tensile strength of the mercerised cotton fibre. Furthermore, the cotton fibres swell as a result of mercerization which causes many of the hydrogen bonds between the chains to break, reducing the ratio between the crystalline and amorphous arrangement to around 1:1 instead of 2:1 (Textile Institute 2007). This reduced ratio renders the fibres more exposed to chemical degradation.

Flax

Flax fibres, which are used to manufacture linen, are extracted from the flax plant *Linum usitatissimum.*The fibres contain cellulose (62-74%), lignin (2-8%), waxes (1-4%), hemi-cellulose (14-22%), pectin (1-2%) although this varies amongst cultivars and due to types of processing (Zimniewska 2015). The average DP of the cellulose is between 10 000-20 000. The 20-50mm long individual fibres (often known as ultimate fibres) are polyhedron tubes which combine to form fibre aggregates of length 450-600mm with an interphase comprised primarily of hemicellulose and pectin (Bos,Oever and Peters 2002; May and Jones 2006).

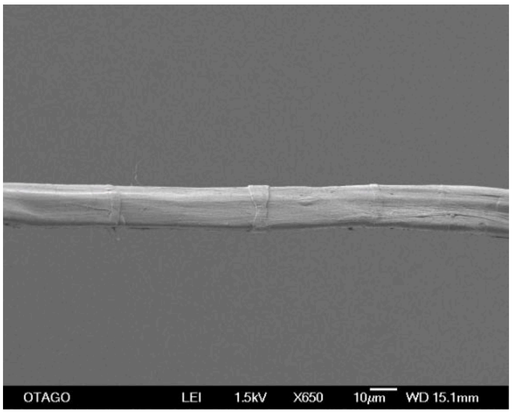


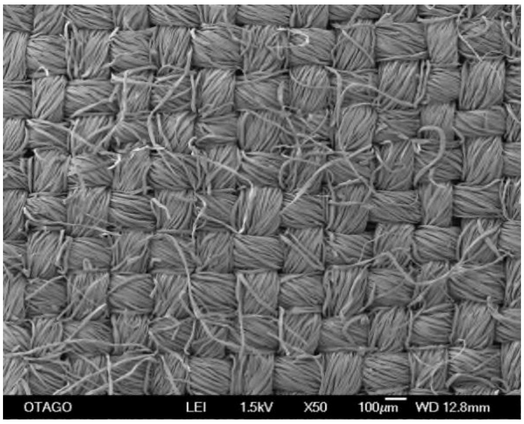
Figure 4: SEM PEL aerolinen, surface of single fibre.
Under magnification, flax fibres appear long with thick walls and kink bands across the fibre. Image courtesy of Liz Girvan, Otago Micro and Nanoscale Imaging, University of Otago.

The modern preparation of flax fibres is mainly mechanical, but biological methods have been used historically and still are in some parts of the world. The outer bark is removed by soaking the stem in water or chemicals to soften it for easy removal (retting). The stem is then beaten, and non-fibre components are removed (breaking and scutching) before drawing the fibre aggregates through pins to separate the fibres before spinning (hackling). The finest flax fibres are produced by pulling the fibre aggregates through increasingly narrowly set pins in order to further separate (Cook 1984).

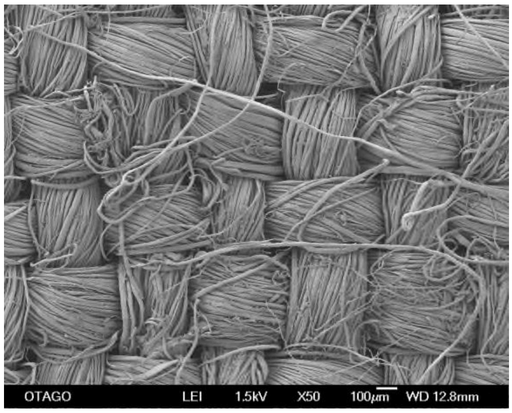
The mechanical beating also produces physical defects across the fibres known as kink bands which occur randomly throughout the cellulose fibres (Aslan et al. 2011; Bos, Oever, and Peters 2002) (Fig 4). They can extend across the full width of the flax fibre but are more likely to extend only halfway or be present in the outer layers of the cellulose fibrils (See Fig. 4, SEM of PL). Literature suggests that the kink bands are where flax fibres break when subjected to tensile and compressive forces (Bos, Oever, and Peters 2002; Aslan et al. 2011). The staggered or step-shaped breaks that are produced are specific for flax fibres and can be described as a break between two kink bands with a longitudinal split down the centre of the fibre. A fibre without any or only a few kink bands is more likely to break at the pectin interphases as they will be more easily pulled apart than the undamaged fibre itself and give the appearance of a blunt end (Aslan et al. 2011; Bos, Oever, and Peters 2002).

Woven fabric

Woven fabrics are the result of interlacing yarns manufactured from spun fibres (Denton and Daniels 2002; Fig. 5). The warp direction runs the length of a woven fabric, the weft direction runs across the fabric and the bias direction is at 45 degrees (British Standards Institute 1977). During weaving, warp yarns are placed under greater tension than the weft. When laundered, the shrinkage is affected more by the fabric's woven structure than by the properties of the yarn and the fibres. There is greater dimensional change in the warp direction as these yarns are subjected to a higher tension during weaving (Collins G.E. 1939).



(a) SEM Friebe aerocotton.



(b) SEM PEL aerolinen.

Figure 5: Comparative SEM images showing aerocotton and aerolinen in the woven state and the individual fibres. Images courtesy of Liz Girvan, Otago Micro and Nanoscale Imaging, University of Otago.

Materials and methodology

In 2017, the Oxford Conservation Consortium (OCC) and the Bodleian Library Conservation and Collection Care Department outlined the scope of the project. In collaboration with Cranfield University, seven sets of data were collected. Measurements of mass, thickness and sett (thread count) were taken for each fabric. The tensile strength and elongation were tested to compare the fabrics and confirm their suitability for use in book and manuscript conservation. A folding endurance machine was used to assess each fabric's folding endurance. Unlike the bespoke machine used by Dorning (Dorning 2005), the tests were not tailored to imitate the precise action in a binding, but rather to test the fabrics in terms of relative strength and durability according to scientific standards. The final test looked at the dimensional stability of each fabric, recording dimensional change after multiple laundering cycles.

Two sources of linen and three of cotton woven fabrics were used in these experiments: Arville linen (AL), PEL linen (PL), Arville cotton (AC), Friebe cotton (FC), and Samuel Lamont cotton

(SC)(discontinued). Table 1 lists the fabric properties as provided by the suppliers, showing the difference among the products. Lamont could not provide independent test data for their 2006 cotton; however, they state that it was produced in line with the BSI standard for aerospace materials (Marrs 2018). These figures, taken from the standard, have been marked with an asterisk.

Table 1: Fabric properties as provided by the supplier.

Fabric	Width (mm)	Mass per unit area (g/cm2)	Number of threads per cm		Finishing	Tensile strength (N/50mm)_	
			Warp	Weft		Warp	Weft
Arville linen (AL)	1370	148	29	30	Calendered	600	700
Preservation Equipment Ltd linen (PL)	1730	180	Not supplied	Not supplied	De-sized and scoured, assisted and calendered	Not supplied	Not supplied
Arville cotton (AC)	1220	140	32	29.5	Scour and Heat Set	650	650
Friebe Luftfahrt-Bedarf cotton(FC)	1370	148	29	30	Calendered	478	543
Samuel Lamont & Sons Ltd. (purchased 2006) cotton (SC)	1730	180	31*	32*	De-sized and scoured, assisted and calendered	700*	785*
Specifications for loomstate and cropped linen (BS 7F 1:1992)		160	29	31		680	725
Specifications for loomstate cotton (BS 7F 8:1992)		150	31	32		700	785

It was noted that the fabrics in an as-received condition had different handling characteristics to each other. All the fabrics had been subjected to a calendering process, giving a smooth finish. An offcut of each fabric was tested for starch using iodine, but no starch was found suggesting no presence of a starch-based finishing treatment. Tests were conducted on not laundered and laundered specimens of each fabric. The laundering process washed the fabrics twice at 90°C using a washing machine (Bosch VarioPerfect, type WCM62) with a 1400 spin, no detergent, and each cycle lasted two hours and 35 minutes. The fabrics were not left to dry between cycles, but afterwards were hung to dry and ironed. For each test (except dimension change) 5 samples of both laundered and not laundered fabric were cut so as not to share the same warp or weft yarns. Where this was not possible due to limitations in fabric size, the overlaps were documented. The samples were labelled with unique identifiers in graphite and all the tests were conducted with the samples parallel to the direction stated.

Mass per unit area, thickness, sett

Samples were cut 100 x 100 mm and were conditioned in an HCC019.PF4.F Sanyo Gallenkamp PLC environmental chamber to 20°C (±2°C) and 65%RH (±4%) for a minimum of one hour according to ISO 139:2005 (British Standards Institute 2011a). Each sample was weighed using an Oxford A2204 analytical balance to determine the mass and mass per unit area according to BS EN 12127:1998 (British Standards Institute 1998). The thickness was measured using a Mitutoyo thickness gauge according to ISO 5084:1997 (British Standards Institute 1997). Sett was determined according to BS 1049-2:1994 (British Standards Institute 1994).

Tensile test

Samples were cut 50 mm wide (±0.5 mm) by 300 mm long (±1 mm) with a 5 mm fringe on the long edges in each of the following directions: warp, weft and bias and the gauge length were 200 mm (British Standards Institute 2013). To achieve the fringe, the yarns were teased out using a needle. This was to ensure that each sample had the same width of continuous unbroken yarns. Before testing, samples were conditioned in the Sanyo Gallencamp PLC environmental chamber for a minimum of one hour according to BS 139:2005 (British Standards Institute 2011). A bench-mounted Instron 557 running in tensile mode with Bluehill 2 software was used to collect force-extension data.

Folding endurance

Samples were cut 15 x 100 mm in each of the following directions: warp, weft and bias. Samples were conditioned in an environmental chamber for a minimum of one hour (British Standards Institute 2011a). The machine used was an MIT fold endurance machine, model number 20013/9. The environmental control was provided by a Calorex Century Series 4 evaporative humidifier, model H12C UKO, and the conditions were recorded using a Hanwell datalogger. After conditioning, the sample was placed in the machine in accordance with ISO 5626:1993 (International Organisation for Standardization 1993). The plunger was operated using the gauge, set to 10.5 N. It is acknowledged that this differed from the standard for paper (ISO 5626:1993), however as the samples tested were fabrics, they required a higher tension.

The machine was switched on, with the start time and date recorded, and ran until the fabric broke, at which point the number of double folds was recorded. The folding endurance was calculated as the $\log_{10}$ of the number of double folds required to cause rupture of the sample. Due to logistical limitations, it was not possible to have the machine running continuously overnight. In the instances where a sample took longer than seven hours to reach a breaking point, the machine was paused overnight. The humidifier was switched off, and the textile de-tensioned without removing it from the clamps. The following day the humidity and temperature were once again brought to the required level before resuming the test.

Dimension change

The dimension change on laundering was investigated using three samples from each as-received fabric, cut a minimum of 100 mm from the selvage edge (with reference to ISO 13934-1:2013 (British Standards Institute 2013)) and measuring 300 x 300 mm. This dimension differed from the standard but was chosen to ensure no overlap of warp and weft yarns (British Standards Institute 2008). Each sample was given a unique identifier in permanent marker.

As described in ISO 3759:2011 (British Standards Institute 2011b) all samples were overlocked along all edges to avoid unravelling, and marks for measuring were hand sewn on the sample as shown in Fig. 6, giving three warp and weft measurements between each pair of points. All sewing used a polyester thread to avoid any unwanted shrinkage of edges and marks.

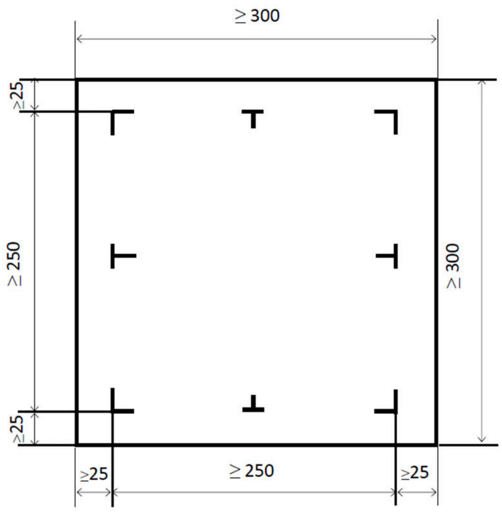


Figure 6: Marking of fabric specimens, dimensions are in millimetres (British Standards Institute 2011b).

The washing and drying (laundering) process for dimensional stability assessment followed in-house methods used at OCC and Bodleian Libraries. The samples were conditioned in a humidity chamber for 24 hours before measuring and recording each distance (British Standards Institute 2011a). All samples were treated at the same time and boiled in 7 L tap water with 10 ml detergent (METAPEX 38, Liquid) for 15 minutes. The samples were rinsed three times in tepid water, before being lightly wrung. In accordance with ISO 6330:2012, the samples were then smoothed out by hand and left to dry flat on blotters (British Standards Institute 2012). The following day, the dry samples were ironed and re-conditioned in the humidity chamber overnight. All six measurements (three warp and three weft) for each sample were then recorded again. This method of boiling, rinsing, drying, ironing, conditioning and measuring was repeated a total of six times.

Analysis

The effect of fabric type, treatment (not laundered or laundered) and specimen direction (warp, weft, bias) on each of the tests was assessed using univariate analysis of variance (ANOVA; IBM®

SPSS® Statistics v24). Homogeneity of variance and normality of residuals were checked. Tukey's HSD (Honest Significant Difference) post-hoc test was used to identify groupings when ANOVA returned a significant result. When Mauchly's test of sphericity was significant, the Greenhouse-Geisser correction was used. Main effects and significant interactions only are discussed in the results section.

After testing, all the samples were observed both unaided and under magnification (Wild Leitz microscope, Wild M8 model with a 1.0x objective lens, fitted Lumenera Infinity 3 camera) at both x25 and x50 magnification in order to compare the physical characteristics of the breaking points, or 'failure modes'. These observations were descriptive and subjective, and loosely categorised each sample by the type of break, the number of breaks, and the change in shape. Observations examined both the break in the yarn, and the fibre break.

Results

Physical properties

Table 2: Mean and standard deviation data for the thickness, mass per unit area and sett of each fabric.

		Mass (g)		Thickness (mm)		Mass (g) per m^2		Sett/2 cm (warp)		Sett/2 cm (weft)	
Fabric	Treatment	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
AL	Not laundered	1.46	0.02	0.18	0.01	145.97	1.91	56.00	0.71	55.40	1.14
	Laundered	1.65	0.02	0.27	0.02	165.00	2.03	59.60	0.55	58.00	1.00
PL	Not laundered	1.87	0.02	0.26	0.02	186.81	2.39	42.40	0.55	42.20	0.45
	Laundered	2.07	0.03	0.34	0.02	206.52	2.92	44.00	0.71	45.00	1.00
AC	Not laundered	1.47	0.00	0.22	0.01	146.85	0.45	63.00	0.71	62.80	0.84
	Laundered	1.60	0.02	0.26	0.01	160.47	1.71	66.40	0.89	67.00	0.71
FC	Not laundered	1.13	0.01	0.13	0.01	113.47	0.91	90.00	1.22	81.60	1.14
	Laundered	1.23	0.01	0.18	0.01	123.13	0.74	90.60	0.89	89.40	1.82
SC	Not laundered	1.39	0.01	0.15	0.01	139.43	0.96	60.60	0.55	60.60	0.55
	Laundered	1.54	0.02	0.23	0.02	154.20	2.06	64.20	0.45	66.60	1.52

Thickness

Fabric thickness varied due to laundering and among the types of fabrics ($F_{1, 40} = 294.87$, $p \leq 0.001$; $F_{4, 40} = 146.33$, $p \leq 0.001$ respectively). Laundered fabrics were thicker than not-laundered fabrics (mean laundered = 0.26 mm; mean not-laundered = 0.19 mm). Tukey's analysis of fabric thickness identified four groups: PL (mean = 0.30 mm), AL and AC were similar to each other (means = 0.22 mm, 0.24 mm respectively), SC (mean = 0.19 mm) and the thinnest fabric was FC (mean = 0.16 mm).

Change in fabric thickness due to laundering varied among the fabrics ($F_{4, 39} = 4.74$, $p \leq 0.01$): AC (15%), PL (23%), FC (27%), AL (33%), SC (35%).

Mass per unit area

Fabric type and laundering affected mass per unit area ($F_{4, 40}$ = 2209.08, p ≤ 0.001; $F_{1, 40}$ = 674.93, p ≤ 0.001 respectively). The lightest fabric was FC (mean = 118 g/m^2), SC (mean = 147 g/m^2), AL and AC were similar to each other (means = 155 g/m^2 and 157 g/m^2 respectively) and PL was the heaviest fabric (mean = 197 g/m^2). Laundered fabrics were heavier than not-laundered fabrics (means = 162 g/m^{2}and 148 g/m^2 respectively).

Laundering affected mass per unit area differently among the fabrics ($F_{4, 40}$ = 23.96, p ≤ 0.01). All laundered fabrics were heavier than not-laundered fabrics by between 8% to 12% except for AC which only increased in mass per unit area by 4%.

Sett

Both AL and PL had the lowest sett (thread count) of the fabrics (not-laundered mean warp = 56; mean = 42 respectively), whereas FC had the highest (mean = 90). Across all the fabrics, the warp sett per 2 cm increased between 4-6% after laundering except for FC that only increased 1%. In the weft direction, all fabrics had a sett increase after laundering of 5-10%.

Dimensional stability

All fabrics shrank after six laundering cycles in both the warp and weft directions compared to the original dimensions (Table 3). Repeated measures ANOVA indicated that this dimensional change was significant ($F_{3.26, 65.25}$ = 2694.95, p ≤ 0.001).

Mean, standard deviation and percentage change of warp and weft measurements for the first and last laundering cycles are provided in Table 3.

Table 3: Selected data showing the dimension change after one laundering cycle.

		Not laundered		Laundering cycle 1				Laundering cycle 6		Total dimension change	
Fabric	Direction	Mean (mm)	SD (mm)	Mean (mm)	SD (mm)	Mean (%)	SD (%)	Mean (mm)	SD (mm)	Mean (%)	SD (%)
AL	Warp	251.06	0.46	225.28	1.64	-10.27	0.64	224.17	1.48	-10.71	0.49
	Weft	250.94	0.30	237.33	1.22	-5.42	0.50	232.17	1.00	-7.48	0.43
PL	Warp	250.72	0.44	231.17	1.89	-7.80	0.68	226.83	1.70	-9.53	0.65
	Weft	250.94	0.39	239.28	2.29	-4.65	0.83	237.39	1.27	-5.40	0.44
AC	Warp	251.00	0.25	237.44	1.40	-5.40	0.50	233.06	1.10	-7.15	0.39
	Weft	250.94	0.58	241.72	1.44	-3.68	0.49	238.11	1.39	-5.11	0.48
FC	Warp	251.39	0.39	237.89	1.83	-5.37	0.51	232.11	2.07	-7.67	0.64
	Weft	251.17	0.56	245.83	0.97	-2.12	0.32	242.39	0.93	-3.50	0.21
SC	Warp	251.33	0.61	235.78	1.73	-6.19	0.55	230.83	1.52	-8.16	0.45
	Weft	250.75	0.71	242.11	1.47	-3.43	0.45	239.94	1.21	-4.30	0.32

Univariate ANOVA identified that direction (warp, weft) and fabric type affected the magnitude of the shrinkage measured after six laundering cycles compared to the original dimensions ($F_{1, 20}$ = 1646.40, p ≤ 0.001; $F_{4, 20}$ = 300.12, p ≤ 0.001). A larger amount of shrinkage was identified in the warp direction (mean = 8.7%) compared to the weft direction (mean = 5.2%). Tukey's analysis identified four fabric groups with respect to dimensional change: the greatest amount of shrinkage from the original dimension (mean = 251 mm) occurred for AL (mean dimension after 6-cycles = 232 mm), PL (mean dimension after 6-cycles = 235 mm), SC and AC were similar (means = 238 mm and 239 mm respectively) and the smallest amount of change was for FC (mean dimension after 6-cycles 241 mm).

Tensile testing

Force-at-rupture

Force at rupture results are shown in Figure 7.

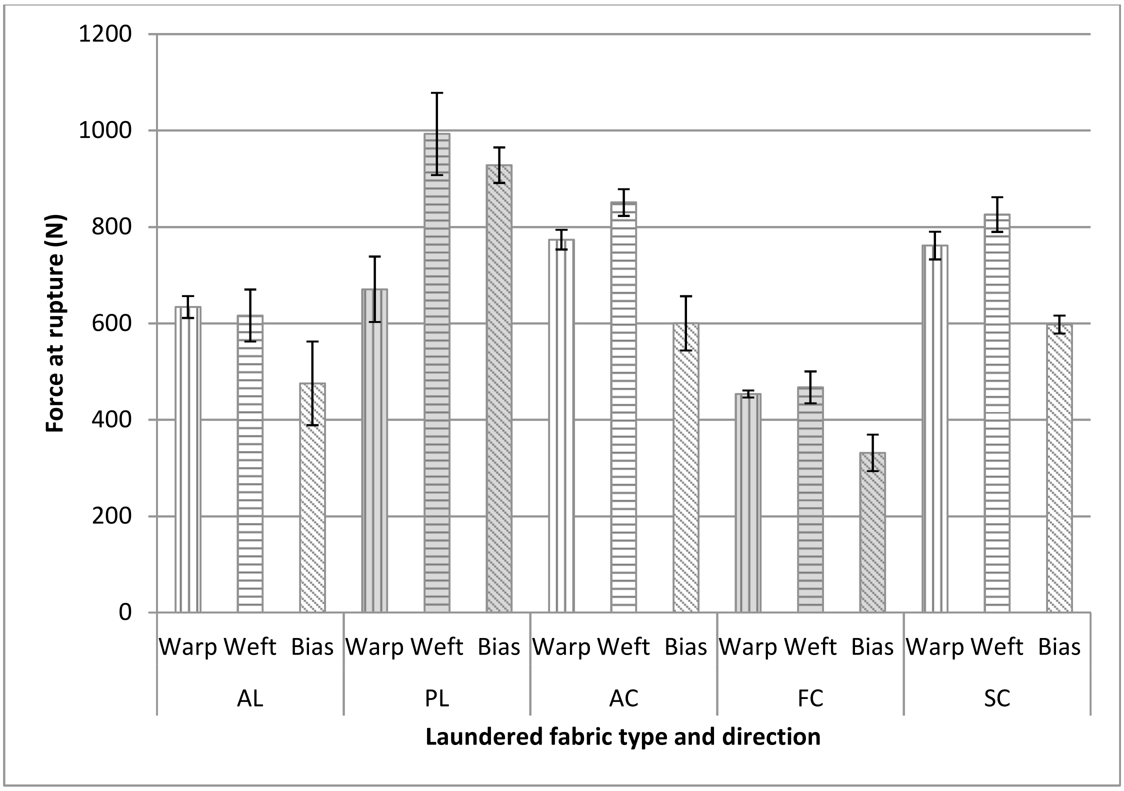


Figure 7: Tensile test results showing the force at rupture of laundered fabrics in three directions.

ANOVA identified that fabric type, treatment and specimen direction all significantly affected force-at-rupture ($F_{4, 120}$ = 481.41, $p \leq 0.001$; $F_{2, 120}$ = 279.20, $p \leq 0.001$; $F_{1, 120}$ = 4.97, $p \leq 0.05$ respectively). Tukey analysis grouped the fabrics into four subsets (strongest to weakest): PL (mean =889.34), AC (708.31) and SC (696.24) were similar to each other, AL (578.88), FC (413.82). Laundered fabrics were slightly stronger across all other variables than not-laundered fabrics (665 N; 649 N). Weft direction specimens were the strongest and bias direction the weakest (mean weft = 745 N; mean warp = 684 N; mean bias = 543 N).

The effect of treatment varied due to the direction the specimen was cut in ($F_{2, 120}$ = 30.61, $p \leq$ 0.001). The bias direction specimens were the weakest, irrespective of treatment, except for PL where the laundered bias direction was stronger than the laundered weft (see figure 8). The strongest specimens were those cut in the weft direction irrespective of treatment.

The direction in which the specimens were cut affected the strength of the fabric differently ($F_{8, 120}$ = 19.34, $p \leq 0.001$). For all fabrics, apart from laundered PL, the bias direction was the weakest direction. For all fabrics except AL, the weft direction was stronger than the warp direction although the mean values were similar for FC.

Finally, the effect laundering had on strength varied due to fabric type ($F_{, 120}$ = 9.67, $p \leq 0.001$). Laundered AC, SC and FC fabrics were stronger than not-laundered specimens (although FC laundered was similar in strength to not-laundered specimens). PL and AL were stronger when not-laundered (although not-laundered AL was similar in strength to laundered AL).

Elongation

Elongation results are shown in Figure 8.

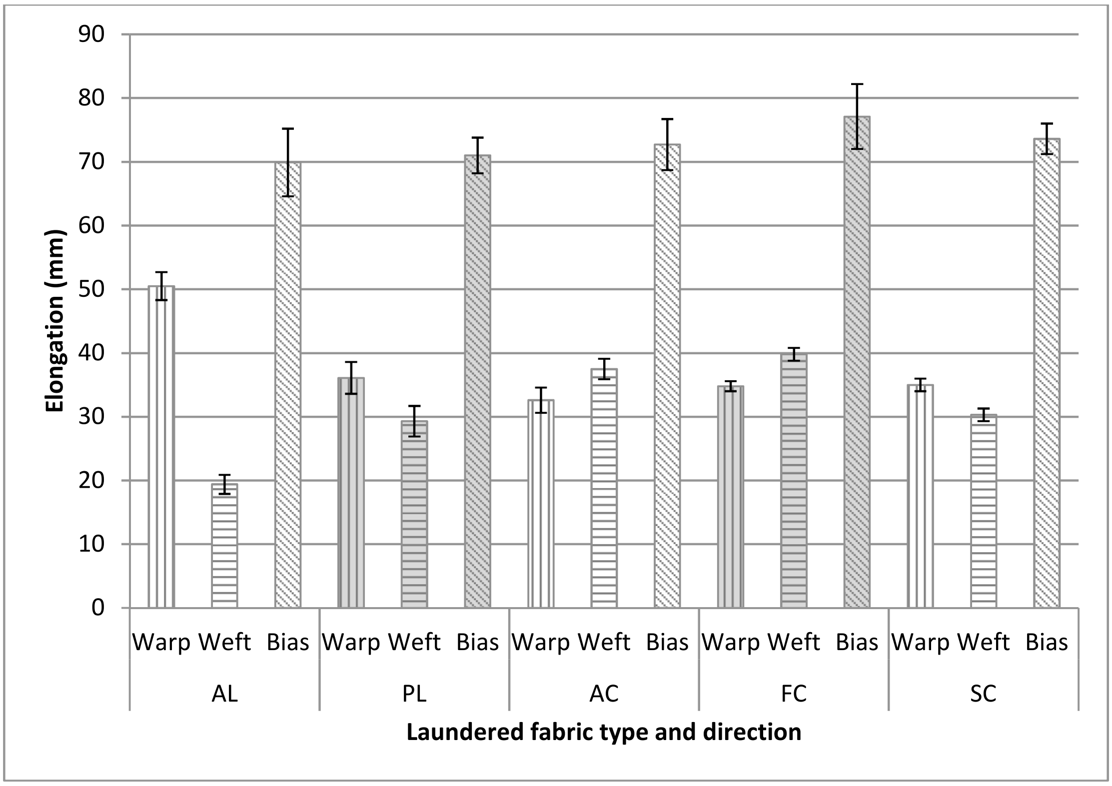


Figure 8: Tensile test results showing the elongation of laundered fabrics in three directions.

ANOVA identified that direction, treatment and fabric type all significantly affected elongation ($F_{2, 119}$ = 4313.00, $p \leq 0.001$; $F_{1, 120}$ = 412.04, $p \leq 0.001$; $F_{21, 120}$ = 4.00, $p \leq 0.001$ respectively). The largest mean elongation was observed for bias specimens (70 mm) and the smallest for weft specimens (29 mm). Although mean elongation for warp specimens was (31 mm) placed in a separate Tukey HSD Group, it was similar to weft specimens. Not-laundered specimens had a lower mean elongation than laundered specimens (39 mm and 47 mm respectively). Tukey analysis identified three groups for fabrics: the highest elongation was for FC (47 mm), AC had a mean elongation of 44 mm, fabrics AC, PL and SC had a similar mean elongation (41 mm, 42 mm, 42 mm respectively).

The direction the specimens were cut in affected the elongation of the fabric differently ($F_{8, 119}$ = 90.87, $p \leq 0.001$). For all fabrics, the bias direction extended the most. Warp direction fabrics extended the least for AC and FC; and fabric SC had the same mean elongation as measured in both the warp and weft directions. For fabrics PL and AL, the lowest mean elongation was in the weft specimens (see figure 9 for a comparison of laundered specimens in each direction).

Whether or not the fabric was laundered affected the elongation in different directions ($F_{2, 119}$ = 42.49, $p \leq 0.001$). The largest mean elongations were measured for laundered specimens irrespective of direction, however laundering affected the percentage changes in elongation differently according to direction: warp = 35%, weft = 16%, bias = 7%.

The effect laundering had on elongation was also affected by fabric type although to a much lesser amount ($F_{4, 119}$ = 2.69, $p \leq 0.05$). Laundered fabrics extended to a greater amount; for AC, FC, SC and PL this increase was between 15% to 17%; for AL the increase was 23%.

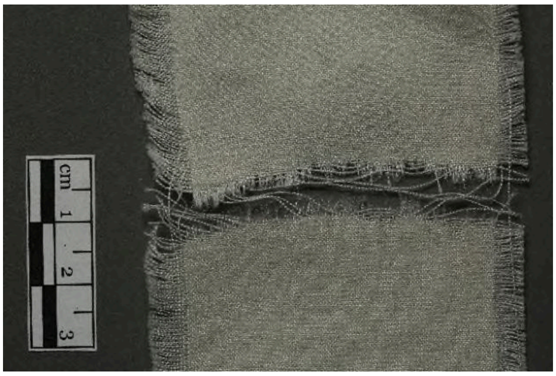
Failure modes due to tensile testing

Fabric type, direction, and treatment all affected the failure mode.

AC typically exhibited a single, straight break across the sample either horizontally or slightly angled (Fig. 9(a)) whereas FC formed jagged lines (Fig. 9(b)). SC showed mixed results, with incomplete breaks (not laundered) and complete breaks (laundered) (Figure 9(c)). Failure modes among AL samples were highly varied, although usually presenting multiple breaking points over a large area and a distorted fabric shape (Figs. 10 (a) and (b)). Similarly, PL did not exhibit clean breaks but multiple small failures over a large area (Figure 11 (a) and (b)).

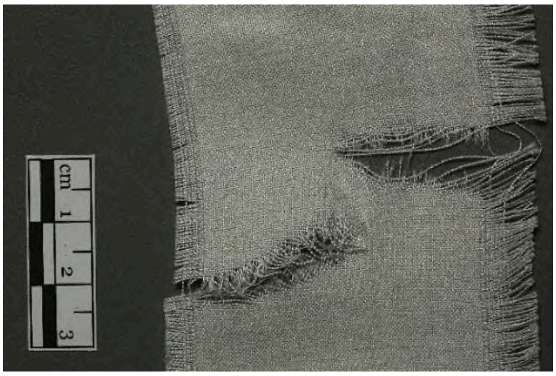
There was little observed difference between the warp and weft directions, with the exception of AL where the weft direction had fewer break points in a more localised area. Laundering did not impact the failure modes of the fabrics, except for SC and PL. Laundered SC samples broke in a continuous line, whereas the not-laundered samples fractured along multiple lines. Laundered PL samples were significantly more uniform in mode of failure, and the breaking points were smaller.

All samples cut on the bias for all five fabrics – not laundered and laundered - behaved in a similar fashion: an angled break in one place with yarns visibly pulled from the fabric. Necking and narrowing (distortion of the fabric under tension) were observed for all bias cut samples (See Figs. 12 (a) and (b)), and almost all the samples were fully broken.



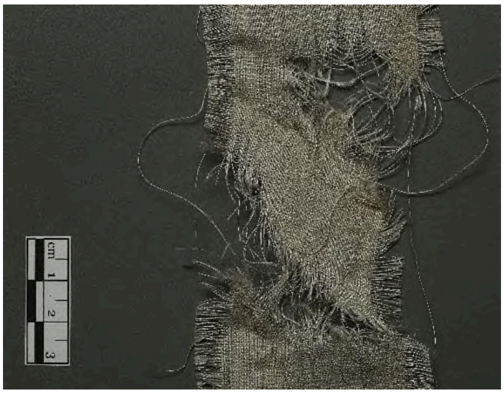
9(a) AC

9(b) FC



9(c) SC

Figure 9: Typical failure modes for the three cotton fabrics subjected to tensile strength test; (a) AC laundered warp; one clear break in a straight line across the samples. Warp, weft, not laundered and laundered samples all followed the same pattern (b) FC not laundered weft; one arrow shaped break across the sample. Warps, weft, not laundered and laundered samples all followed the same pattern (c) SC not laundered weft; all not laundered samples broke in discontinued line, where the laundered samples broke in straight lines across the sample.



10(a)

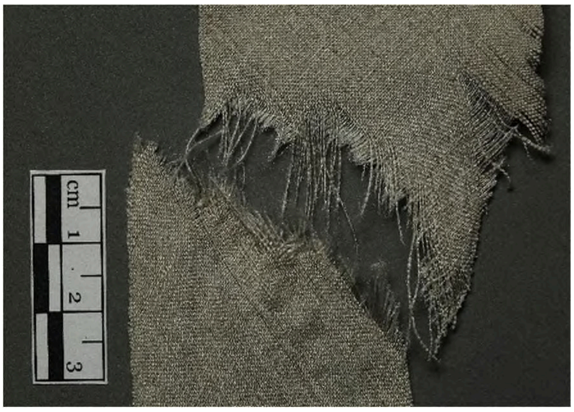
10(b)

Figure 10: Typical failure modes for fabric AL. Similar patterns were observed for both not laundered and laundered samples; (a) AL not laundered warp; breaks in warp samples exhibited a high degree of randomness with large breaks, several breaks of individual yarns and highly distorted samples after testing.(b) AL not laundered weft; a main break across part of the sample with a few broken, individual yarns observed on weft samples.


11(a)


11(b)

Figure 11: Typical failure modes for PL. Similar patterns were observed on both warp samples and weft samples; (a) PL not laundered warp; a larger main break across the sample and a few smaller breaks of individual yarns in the same area (b) PL laundered warp; none of the laundered samples had a main break but exhibited a highly random pattern of several small breaks on individual or small groups of yarns throughout the samples.


12(a) AL


12(b) AC

Figure 12: Typical failure mode for samples cut on the bias. All samples cut on the bias narrowed in the area between the clamps due to the tension placed on the fabric at a 45^o angle (a) AL laundered bias; both linen fabrics (Al and PL) broke at an angle close to 45^o with a number of yarns being pulled from the fabric instead of breaking. (b) AC not laundered bias; all three cotton fabrics (AC, FC and SC) broke in almost straight lines across the samples with fewer yarns being pulled from the fabric.

Folding endurance

Folding endurance results for laundered fabrics shown in Figure 13.

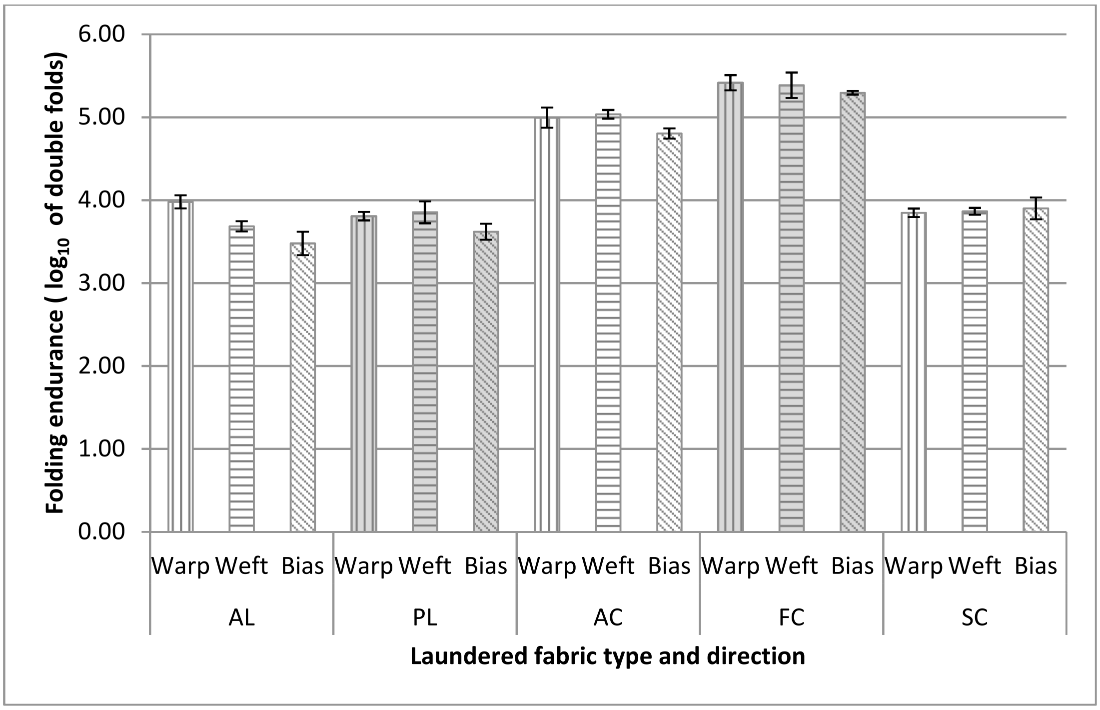


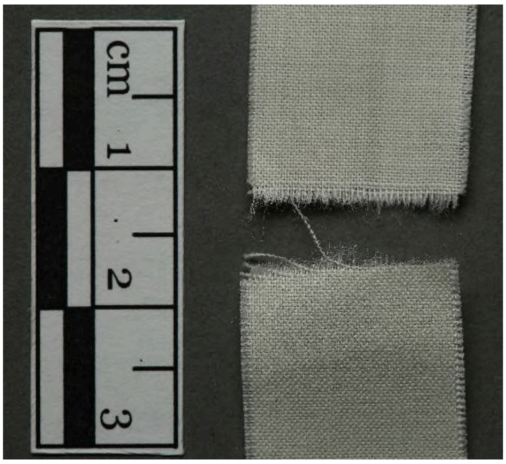
Figure 13: Folding endurance of laundered fabrics in three directions.

ANOVA identified that both fabric type and specimen direction significantly affected folding endurance ($F_{4,\,60}$ = 942.47, $p \leq 0.001$; $F_{2,\,60}$ = 33.583, $p \leq 0.001$ respectively). Tukey analysis grouped the fabrics into five distinct subsets from the most durable to the least: FC, AC, SC, AL, PL. Warp and weft directions were similar and performed best across all other variables, whereas the bias direction was the least durable (mean warp = 4.43; mean weft = 4.37; mean bias = 4.22). Laundering did not have a significant effect on the folding endurance ($F_{1,\,60}$ = 0.75, p =NS) across the variables, but varied according to fabric type ($F_{4,\,60}$ = 12.41, $p \leq 0.001$). After laundering, AL was less durable than PL (means = 3.71 and 3.76 respectively) whereas the other samples remained in the same order of folding endurance.

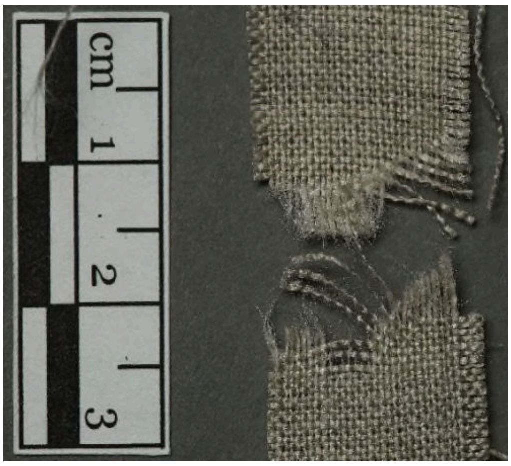
Comparative folding endurance of the laundered fabrics can be seen in Figure 13. Although samples cut on the bias were generally the least durable, the effect of specimen direction varied according to fabric type ($F_{8,\,60}$ = 4.859, $p \leq 0.001$). AL was stronger than SC and PL in the warp direction, but weaker than both in the weft. FC was the strongest in all three directions, followed by AC. SC showed the least difference in strength according to direction, where the bias and weft mean values were similar (means = 3.93 and 3.93 respectively) (figure 5).

Failure modes due to folding endurance testing

Observations on the failure modes showed that fabric type and direction influenced the type of break in the fabric, whereas laundering had no discernible impact. The cottons AC and FC showed a single, straight break across the sample in both warp and weft directions, irrespective of treatment (see fig. 14 (a)). SC showed similar failure modes, but with some uneven breaking points at either side of the sample. PL and AL demonstrated more uneven breaks (see fig. 14 (b)), with staggered failures across the breaking point. In particular, PL exhibited the most irregular breaking points and the most deformation to the sample shape.



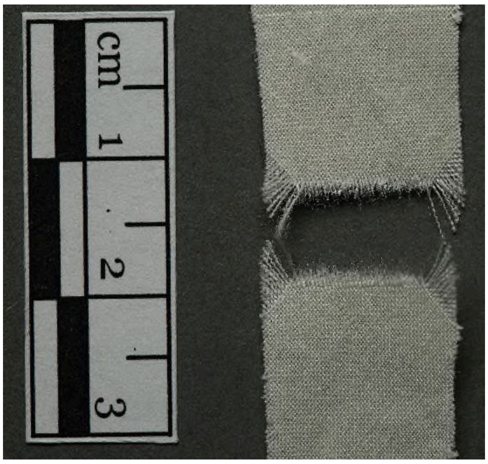
14(a) FC



14(b) PL

Figure 14: Typical failure modes for the three cotton and two linens fabrics subjected to folding endurance test. (a) FC not laundered weft; example of the straight break in the cotton samples (b) PL not laundered weft; high degree of randomness in the break both across the sample and within the individual yarn.

Samples cut on the bias showed significantly different failure modes to those in the warp or weft directions. The samples resulted in significant necking and narrowing in their shape, with a straight break line and whiskers of unbroken yarns on either side (See figs 15 (a) and (b)).



15(a) FC

15(b) AL

Figure 15: Typical failure mode for both cotton and linen samples cut on the bias subjected to folding endurance test. The same type of break was observed for all fabrics: a straight line across the sample and the shorter yarns at edges pulled to give a whisker-like appearance. (a) FC laundered bias (b) AL laundered bias.

Discussion

A comprehensive comparison of fabrics used in book conservation has not been previously reported. The results show that although there was significant variation between fabric treatment, direction, and manufacture, all the fabrics tested were strong and durable and suitable for conservation treatments. The following discussion will summarise some of the key findings and explore their impact on conservation choices.

Treatment

Across all the fabrics, the as-received condition exhibited a highly calendered surface texture and handle, with a lower sett, mass per unit area and thickness than after laundering. The process of laundering changed these physical characteristics, imparting a rougher surface texture, causing a dimensional change and an increase in sett, mass per unit area, and thickness of the fabric. Prior work has also reported such changes in physical and mechanical properties due to laundering (Gore et al. 2006). A substantial dimensional change occurred due to laundering; for the linens most of this happened after the first cycle of laundering. In comparison, for the cottons, there was a steady shrinkage over multiple cycles for all the cotton fabrics demonstrating that more than one laundering cycle may be necessary to achieve dimensional stability (Gore et al. 2006). These observed behaviours can be partly explained by the different properties of cotton and flax fibres. The convolutions in the cotton fibres continue to re-twist when exposed to water, causing dimensional change but can also be related to other fabric structural properties (Collins 1939). All fabrics exhibited greater dimensional change in the warp rather than in the weft, probably due to the fact that the warp yarns are put under greater tension during weaving (Collins 1939).

Fabric orientation

The bias direction was the weakest in both the tensile and folding endurance tests and demonstrated increased elongation. The only exception was PL in the bias direction that had a greater tensile strength than the warp. The authors acknowledge this anomaly, and further testing would be required to draw a conclusion. The weft direction was the strongest for both cotton and linen fabrics. Fabric strength was primarily affected by the number of yarns in the test direction and the strength of the yarns (influenced by linear density and twist level). With respect to folding endurance the warp and weft directions performed similarly and were more robust than the bias direction.

Fabric type

The woven cotton and linen fabrics investigated in this paper have clear differences in physical properties which might be considered in the context of a specific conservation treatment. The linens had a higher mass per unit area and a lower sett whereas the cottons were lighter, thinner and had a higher sett. FC in particular had the least dimensional change after laundering, indicating that the fabric was the most dimensionally stable of those tested. Tensile testing did not comprehensively suggest that one type of fabric (cotton vs. linen) was stronger than the other, but one of the linen fabrics (PL) was the strongest fabric tested. This may be due to its greater thickness and mass per unit area which combined with a relatively low sett suggested higher linear density and hence stronger yarns had been used to manufacture this fabric. However, the linen fabrics had significantly lower folding endurance than the new cotton fabrics. This may be due to the recognised higher brittleness of flax fibres than cotton fibres. The naturally aged cotton fabric (SC) was weaker than the other cotton fabrics despite the fact that physical properties of mass per unit area, thickness and sett were similar across all the cottons. However, these results do not correlate with the existing published data on the same source of cotton (Zimmern 2000). This raises the question of whether the fabric has deteriorated over time. Further testing would be necessary to assess the impact of natural ageing on each of the fabrics.

Conclusion and conservation implications

Conservators have not always laundered fabric prior to use and washing methods have varied. Although all the fabrics were tested for starch with negative results, washing the fabric is advisable as it will help remove any impurities or additives particularly when precise information about manufacture is unknown. Conservation treatments often involve moisture, for example, through the use of water-based adhesives or toning processes and laundering prior to treatment will also minimise any shrinkage that may occur during or post treatment.

Across all fabrics the orientation had a significant impact on behaviour. Although fabrics cut on the bias are often valued for their flexible properties, being more easily moulded and stretched, in all the tests the bias-cut samples performed less well. This suggests that it might be preferable to work with fabrics in the warp or weft direction when carrying out a repair rather than on the bias.

The choice between cottons and linens is less clear cut than weave orientation. The greater weight and strength of the linens (i.e. PL) may make this a more obvious choice when treating a large volume with heavy boards where strength of repair material could be prioritised over other qualities. In addition, it is likely in this context that a larger book could more easily accept heavier or more bulky repair materials. In a similar vein, in the case of small volumes with light structures and materials of construction, it may be the case that the choice of thin, strong cotton (i.e. FC) is indicated.

The fold endurance results clearly showed that the cotton fabrics were more durable but in terms of practical conservation it is unlikely that in use they would ever be subjected to the high number of folds required by the testing standards or indeed a 180° fold. While the cottons outperformed the linens in fold endurance testing, the linens were also strong and durable, and both are suitable for conservation treatment. Selecting repair materials is individual to each conservation treatment. Woven fabrics are chosen for their strength, flexibility and because of a comparatively long history of use as spine lining material and for board attachment Furthermore, the durability of a repair will be impacted by other factors including the strength of the adhesive bond, the condition of the historic material, the future use of the treated volume and the environment in which it is stored. This project has sought to assess material properties objectively through standardised, reproducible tests in order to provide data which can be used by conservators in making treatment choices.

Materials

Arville linen L9F1 (AL). Arville Textiles Ltd., Sandbeck, Wetherby, West Yorkshire, LS22 7DQ, UK. https://www.arville.com
887-11057 Archival Aero Linen (PL). Preservation Equipment Ltd., Vinces Road, Diss, Norfolk, IP22 4HQ, UK. https://www.preservationequipment.com
Arville cotton ARVLX C7F8 (AC). Arville Textiles Ltd., Sandbeck, Wetherby, West Yorkshire, LS22 7DQ, UK. https://www.arville.com
Friebe Cotton. Product 55112 (FC). Friebe Luftfahrt-Bedarf GmbH, City Airport, 68163 Mannheim, Germany https://friebe.aero
Samuel Lamont cotton (SC). Old stock from Bodleian Libraries, no longer available.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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